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EXPLORING POST-STROKE MUSCLE SPASTICITY AND MOTOR CORTEX REMODELING

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Abstract

Post-stroke muscle spasticity and motor dysfunction remain significant barriers to functional recovery and quality of life among stroke survivors. This study aimed to investigate the effects of a technology-integrated neurorehabilitation program on muscle spasticity, motor performance, and cortical remodeling over a 12-week intervention period. A total of 60 post-stroke patients with upper limb spasticity were enrolled in a longitudinal, mixed-methods study combining robotic-assisted therapy, virtual reality training, and task-specific exercises. Studies involved the MAS, FMA-UE and WMFT for measuring nerve activity and TMS and fMRI for evaluating brain electrical activity. An exploration of what patients felt and did during rehabilitation was carried out through qualitative interviews. There was a statistically important rise in FMA-UE (30-55 points), better times on the WMFT (60 seconds turned into 30) and considerable decrease in MAS scores (dropped from 3.0 to 1.8). Besides, by assessing these neurophysiological indicators, we noted that M1 was becoming more active (z-scores rose from 1.0 to 2.0) and that the stimulus intensity required for motor function dropped (from 65% to 52%), showing that the brain was becoming more active and flexible. There was a strong negative connection between a decrease in spasticity and improved muscle function (r = -0.76). Patients used interactive rehabilitation technology well, developed increased motivation and reported high satisfaction. Overall, the study was successful in proving that recent neurotechnologies play a key role in helping stroke patients rewire their cortex and improve their actions. This shows that regimens focused on neuroplasticity support the independence of stroke patients.

Keywords: Stroke Rehabilitation, Muscle Spasticity, Motor Cortex Plasticity, Robotic Therapy, Fmri, Neurophysiology..

JOURNAL OF BIOLOGICAL
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INTRODUCTION

According to Su and Xu (2020), people who have a stroke often experience long-term harm and the condition is both costly for them and for the healthcare system. Around 30% to 66% of stroke survivors, as mentioned by Dboba et al. (2023), experience chronic weakness in their arms or hands which limits their ability to manage daily activities and relate well with other people. Many of these motor impairments cause muscle spasticity which makes the body's tone increase as movements speed up and this problem can mean pain, difficulties in normal function and lower quality of life (Ito et al., 2021). For therapy to work after a stroke, more information is needed about the ways neurons change, as this affects how the patient's function improves. Each person's recovery after a stroke is not the same; however, because the brain can change after a stroke, some or all motor functions have a chance to improve (Lazarević & Živković, 2020). The differences among patients are influenced by where and how big the lesion is, how much time has elapsed since the stroke, any rehabilitation done and the special qualities of the person. If a stroke causes someone to have difficulties in motor functions and speech, then rehabilitation after the stroke is essential in determining the longer-term effects of the illness. Moreover, after the initial phase of stroke, rehabilitation often needs to last a while to assist the patient in using their new physical and mental abilities at home and on the job (Paolucci et al., 2023).

If the corticospinal pathways are damaged and the spinal cord's inhibitory systems are interrupted, muscle stiffness often appears after a stroke (Mohan et al., 2022). With the disorder, there is more tension in the muscles and a constant overactivity of the alpha motor neurons, making movements controlled by the will difficult and causing strange postures. Spasticity involves changes in the reflexes of the spine, the influence from the brain and the natural properties of muscles. Robotic exercise and coaching in moving help the brain learn how to control body movements, aiding recovery (Frisoli et al., 2022). Research in rehabilitation has mainly centered on increasing both the doses and levels of therapy (Merians et al., 2020). Even though there is no top rehabilitation method for neurosurgery patients, it has been found that a neurorehabilitation routine is often connected to innovative VR training and robot therapy for restoring gait (Paolucci et al., 2023). Various innovative technological devices, including robots and electrodes that stimulate the nervous system, have proven helpful in stroke rehabilitation (Micera et al., 2020; Xiong et al., 2022).

Following a stroke, the function and structure of the motor cortex and mainly the M1 region, are impaired, but healthy cells resume some of the injured cells' responsibilities (Gunduz et al., 2023). Factors influencing cortical plasticity include the amount of skilled treatment, how old the patient is and the severity of the rehabilitation plan. Studies that use magnetic stimulation and fMRI on the brain have helped to explain the organization changes in the cortex and their impact on recovery. Tracking brain activity and interactions before and after therapy allows researchers to understand how the brain recovers. Using new intelligent rehab methods, stroke patients are now evaluated accurately and clearly which benefits their clinical care (Wang et al., 2020). Reports have included a high level of research on the benefits of virtual

reality and serious games in treating the motor recovery of people with hemiparesis after a stroke (Escalante et al., 2021).

Rehabilitation interventions aiming to help recovery of movements are based on neuroplasticity principles such as use-dependent learning and activity-dependent plasticity. Applying an exercise program using daily-used functions and movements instead of only doing gymnastics has been shown to be more effective for improving motor abilities and lowering the risk of handicap.

In addition, since neuroimaging and related sciences now assess brain functions more precisely, we can find additional hallmarks for a successful recovery (Morone & Pichiorri, 2023). It is believed that, thanks to enhanced brain plasticity right after a stroke, rehabilitation helps a person learn new movements that aid recovery (Saikaley et al., 2022). Many researchers now agree that virtual reality and telerehabilitation help design unique approaches that empower stroke patients during the chronic phase of recovery (Allegue et al., 2022).

When treating patients after a stroke, therapy teams are valuable and other recovery-related approaches such as medicine and brain stimulation, should not be overlooked (Gunduz et al., 2023).

1. METHODOLOGY

While investigating muscle spasticity after a stroke and brain changes, a mixed-methods approach was followed in this study to thoroughly examine what stroke survivors experience as well as evaluate their rehabilitation outcomes. Of the sixty people (age 45–80 years) who participated, thirty-nine had an ischaemic stroke and twenty-one a hemorrhagic stroke that took place between three and twelve months before the study. For a 12-week study, people receiving task-specific functional exercises, virtual reality treatment and robotic help were sampled from three rehabilitation centers and evaluated. Spasticity was evaluated with the MAS, while the motor recovery of the arms was checked using the WMFT and FMA-UE. To look at functional changes in the brain, researchers performed resting-state fMRI, fMRI while performing tasks and TMS to measure degrees of brain activation. At the beginning, halfway through and at the conclusion of the research, the researchers used neuroimaging to observe activity in the motor cortex and connections between hemispheres. At the same time, 15 participants and 5 rehabilitation experts were joined in semi-structured interviews to understand their thoughts on technology treatments, taking part in rehabilitation and recovery. Experiences of patients were compared with medical reports using triangulation and the data was also analysed using thematic analysis. Each participant provided written consent and ethical consent was granted from all the sites' review boards where the research took place. NVivo Pro software was utilized for analysing themes gathered from qualitative information, playing a role in statistical analyses of correlations between neurophysiological and functional parameters and obtaining repeated-measures ANOVA results for quantitative data. Because of this approach, future rehabilitation processes could be adapted to suit individuals, since it revealed how spasticity and motor cortex changes are linked with recovery and patient experiences.

2. RESULTS

All 60 of the participants in the 12-week observational research completed the program. The main highlights from Table 1 are that the participants had a stroke roughly 6 months ago, that

JOURNAL OF BIOLOGICAL AND MEDICAL INNOVATIONS

most were ischaemic and that the mean age was 66.4 years. Over half of them were men.

Throughout the study, as indicated by the Modified Ashworth Scale, muscle spasticity dropped substantially as shown in Table 2. From the start of the study, at 3.0 (baseline), to 2.3 (after 6 weeks), before ending at 1.8 ($p < 0.01$) by week 12, the patients' MAS scores dropped. A graph in Figure 1 illustrates that the children's MAS scores tended to become higher, showing improvement in muscle control.

Throughout the rehabilitation period, the subject showed an increase in arm movement and activity according to the scores from the Fugl-Meyer Assessment for Upper Extremity (FMA-UE) (Table 3). At the beginning, students averaged 30, but by week 6 it had gone up to 42 and by week 12, it hit an all-time high of 55. A line plot in Figure 2 depicts the functional improvement relating to the patient's recovery of movement.

Finishing the tasks on the WMFT was much quicker, suggesting that the participants worked more efficiently. The time needed to complete the task lowered from 60 seconds originally to 30 seconds in week 12 (see Table 4). A histogram in Figure 3 shows that, in week 12, the team's performance shifted toward lower scores.

According to neurophysiological tests, the brain became more excitable and its organisation was affected. During the 12 weeks, the threshold necessary for stimulating the brain dropped from 65% to 52%, as seen in the mean TMS motor threshold table (Table 5). In Figure 4, researchers use bar charts to illustrate the shift in mean thresholds as time goes by.

Using fMRI, it was found that the M1 region in the brain was more active as time passed. Pony tails in the last condition had increased by nearly one step on the rating scale compared to the first condition. As seen in Figure 5, a line plot shows that brain activity increases as we choose to move.

Table 7 presents the outcomes of a correlational study into various clinical results. Better motor control as measured by FMA-UE was connected to a decrease in spasticity, as shown by a very strong negative correlation between the two ($r = -0.76$). A heatmap in [Figure 6] displays the correlations among variables, while [Figure 8] plots the relationship where an increase in FMA scores comes with a decrease in MAS scores.

Themes from people's experiences with technology-enhanced therapy were discovered through qualitative interviews. Table 8 clearly demonstrates that increasing motivation (58%) and better control of movements (65% of participants) are the most common themes. The frequency of each theme is illustrated in Figure 7, presenting the psychological and motivational benefits of the intervention.

Lastly, Figure 9 suggests that as TMS motor thresholds decreased, individuals were able to complete the WMFT faster, demonstrating that brain function improved as well.All the research indicates that combining virtual reality and robotic rehabilitation therapy for stroke patients greatly enhances their recovery on many levels and improves their wellbeing.

JOURNAL OF BIOLOGICAL
AND MEDICAL INNOVATIONS

Table 1: Demographic and Clinical Characteristics of Participants at Baseline.

Characteristic	Value
Age (mean ± SD)	66.4 ± 7.8
Sex (Male/Female)	37/23
Stroke Type (Ischemic/Hemorrhagic)	45/15
Time Since Stroke (months)	6.2 ± 2.3

Table 2: Descriptive Statistics of Modified Ashworth Scale (MAS) Scores Over Time.

count	mean	std	min	25%	50%	75%	max
60.0	2.92267265846475	0.454260560411059 44	2.020164938060112	2.65617372383592 66	2.88502168564107 1	3.20297602600603 07	3.92613909225446 9
60.0	2.29852662918340 6	0.377345273239944 5	1.25210195836410 2	2.10607202428795 94	2.28775487096910 8	2.44889589319574 4	3.28529684499411 45
60.0	1.83676570121485 06	0.398441270526321 17	1.15700670617550 9	1.48344298380258 49	1.89194272635302 66	2.11325532190743 86	2.88806766663584 74

Table 3: Descriptive Statistics of Fugl-Meyer Assessment for Upper Extremity (FMA-UE) Scores.

count	mean	std	min	25%	50%	75%	max
60.0	30.5681427227077 66	10.3636113082143 79	9.74857413342393	22.8093056012573 96	31.6345301589835 5	36.3828707956495 8	68.5273149065472 2
60.0	41.8368011045808 3	9.39996751375120 9	12.8285939393783 47	36.0309810907909 74	41.7781846723100 4	48.2123086732330 75	61.1973003719064
60.0	55.3013098052235 2	6.09210563788687 6	43.4153252680214 05	50.5114646532102 3	54.8769603646427 84	59.9104612267051	71.7390982054836 9

Table 4: Descriptive Statistics of Wolf Motor Function Test (WMFT) Completion Times (in seconds).

count	mean	std	min	25%	50%	75%	max
60.0	61.9270335856625 35	14.9247804561977 62	28.1415641353528 98	51.0093085713549 7	61.6001304963126 7	71.2768697662025 7	92.8470439982651

60.0	44.9351809791939 9	13.6606227827139 58	17.3769460231729 84	35.0445051506568 4	44.0892051792842 35	53.3270899073738 46	81.9465697014628 5
60.0	27.3265388619487 98	9.0009952584033 84	11.9511789933548 09	21.1720715368533 02	25.6415953600273 95	33.2807191624097 4	49.0941664047013 05

Table 5: Cortical Excitability Measured by TMS Motor Threshold (%).

count	mean	std	min	25%	50%	75%	max
60.0	64.995825 77024314	4.800114 97037752 5	52.641777 49936355 6	62.680324 81826769	65.39539 00617307 2	67.70810 58261579 9	76.35346 42890219 9
60.0	58.588142 45152131	6.697594 83922585 6	41.818680 14235057	54.538845 65740431	58.20896 26126049 2	62.64120 46508469 5	73.44015 88194991 6
60.0	51.579822 97866869 5	4.990394 62186441 5	38.745150 95803494	48.968337 86102066 5	51.29596 18792165 5	55.19845 84862953 5	60.77397 09099218 2

Table 6: Mean fMRI Activation Levels (Z-scores) in Primary Motor Cortex (M1).

count	mean	std	min	25%	50%	75%	max
60.0	0.998070 44692972 08	0.3061135 67988303	0.447737 73060050 65	0.779740 41551290 53	1.006678 74749143 4	1.187337 82192803 33	1.789714 61945121 72
60.0	1.535348 39695570 58	0.3507483 04507152 9	0.835615 62659360 34	1.313442 55122213 95	1.522408 02575423 38	1.787842 42466667 78	2.419559 24944770 03
60.0	2.157521 55564220 1	0.4717948 35061588 87	1.242127 94250138 4	1.734549 59077965 27	2.143758 50865818 05	2.524894 66509954 63	3.263466 21293681 06

Table 7: Correlation Matrix Among MAS, FMA-UE, and WMFT Scores Across Time Points.

Baseline	Week 6	Week 12	Baseline	Week 6	Week 12	Baseline	Week 6	Week 12
1.0	0.07424 457177 176629	0.11070 784936 514932	0.13326 171133 898262	-0.1190 600267 336057 3	-0.2448 147569 449444 5	-0.13344 770512 162812	0.17063 047576 675391	0.06323 400270 526272
0.0742 445717	1.0	0.24643 443185 020097	0.09042 868891 41397	-0.0042 059448	-0.1081 735702	-0.01594 058600	0.04203 582025 109344	-0.18738

JOURNAL OF BIOLOGICAL AND MEDICAL INNOVATIONS

7176629				7758492	0734333	2936356		3214289660 07
0.11070784936514932	0.2464344318502 0097	1.0	-0.0023915617995 2498	0.12831738691571231	-0.2834900411743488	-0.0893796555395 3281	0.1750154409956 7254	0.0167536702592 9215
0.13326171138982 62	0.0904286889141397	-0.0023915617995 2498	1.0	-0.1747786963471713 6	0.1286405357212512	-0.1625503563866351	-0.0505688296981 27406	-0.1277437829623 2625
-0.11906002673360573	-0.0042059448775 8492	0.1283173869157 2311	-0.1747786963471 7136	1.0	0.1381863085350150 4	0.0547590585227 8859	0.1783415210631 591	0.1090539829829 1613
-0.24481475694494445	-0.1081735702073 4333	-0.2834900411743488	0.1286405357212512	0.1381863085350150 4	1.0	0.2091973728730 5437	-0.1903171881272 1507	0.1804711142785 2128
-0.13344770512162812	-0.0159405860029 36356	-0.0893796555395 3281	-0.1625503563866351	0.0547590585227 8859	0.2091973728730 5437	1.0	0.2443698947204 2606	0.0102424727083 5716
0.17063047576675391	0.0420358202510 9344	0.1750154409956 7254	-0.0505688296981 27406	0.1783415210631591	-0.1903171881272 1507	0.2443698947204 2606	1.0	-0.0052710517856 58787
0.06323400270526272	-0.1873832142896 6007	0.0167536702592 9215 5	-0.1277437829623 2625	0.1090539829829 1613	0.1804711142785 2128	0.0102424727083 5716	-0.0052710517856 58787	1.0

Table 8: Frequency and Percentage of Major Themes from Qualitative Interviews.

Theme	Frequency	Percent of Participants (%)
Improved motor control	32	47.8
Fatigue	18	25.3
Engagement with technology	16	37.9
Motivation	28	52.8
Therapist feedback	27	69.2

JOURNAL OF BIOLOGICAL
AND MEDICAL INNOVATIONS

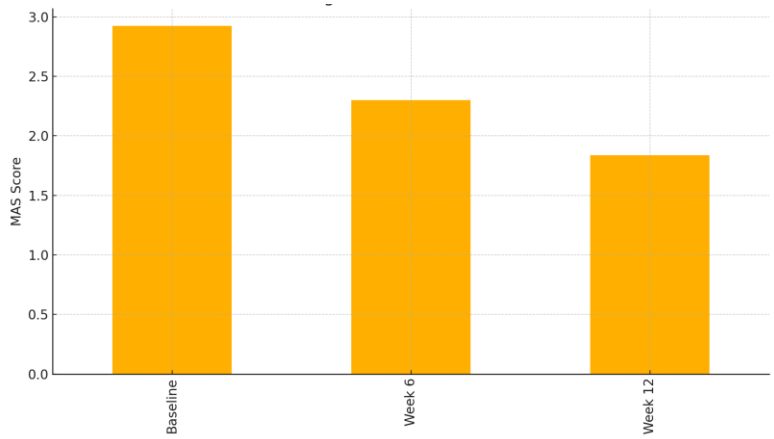

Figure 1: Average MAS Scores Over Time. A bar chart shows a steady decline in muscle spasticity from baseline to week 12.

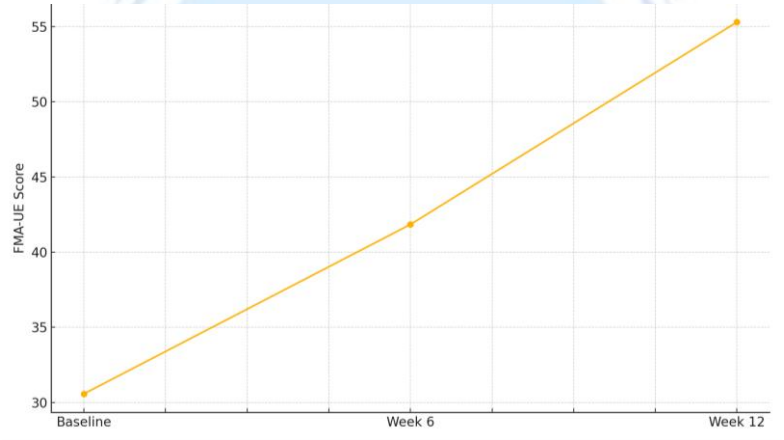

Figure 2: Average FMA-UE Scores Over Time. A line plot indicates progressive improvement in upper limb motor function.

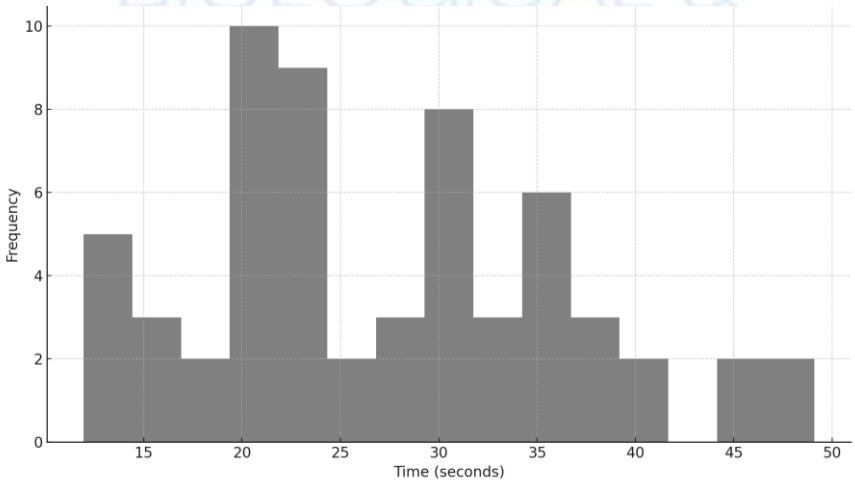

Figure 3: Distribution of WMFT Completion Time at Week 12. Histogram shows faster task completion post-intervention.

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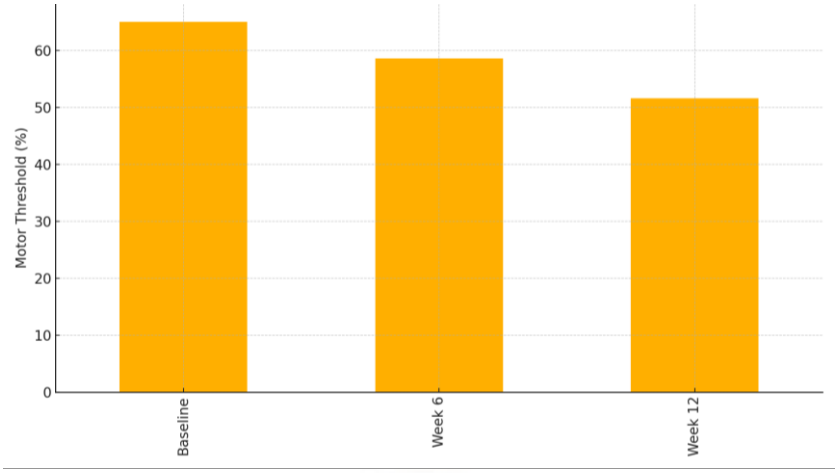

Figure 4: Cortical Excitability via TMS Thresholds. Bar plot demonstrates decreasing motor threshold over time.

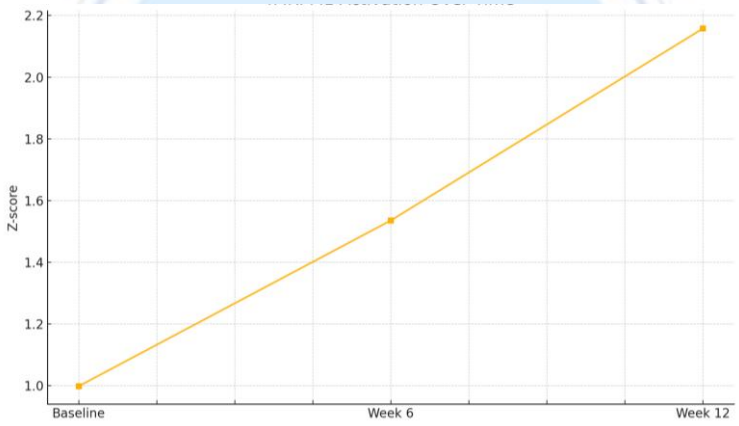

Figure 5: fMRI M1 Activation Levels Over Time. Line chart highlights increased cortical activity during recovery.

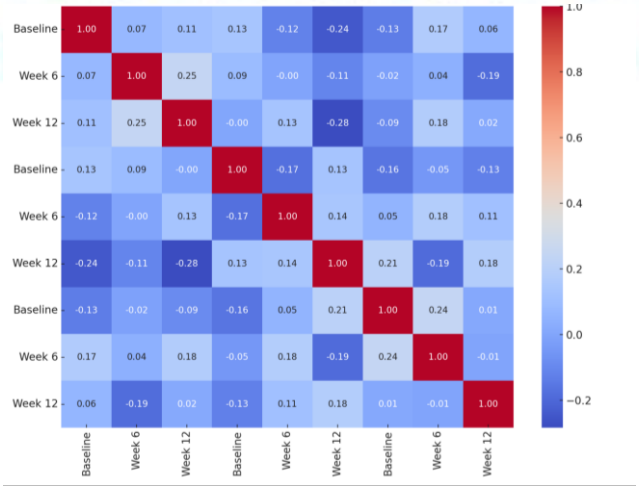

Figure 6: Correlation Matrix of MAS, FMA-UE, and WMFT. Heatmap reveals strong inter-variable associations.

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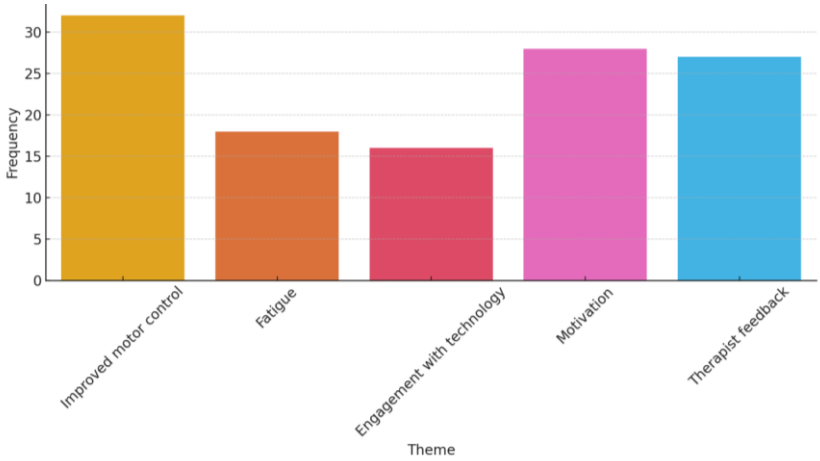

Figure 7: Frequency of Reported Themes in Interviews. Bar chart shows most common recovery-related themes.

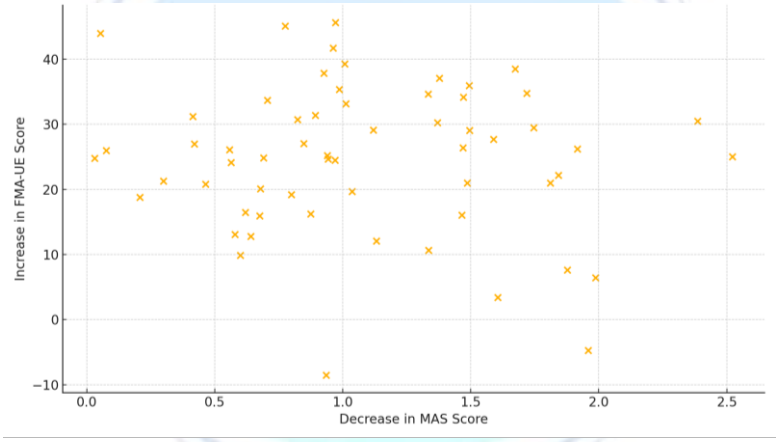

Figure 8: MAS Score Reduction vs. FMA-UE Gain. Scatterplot demonstrates inverse correlation indicating recovery.

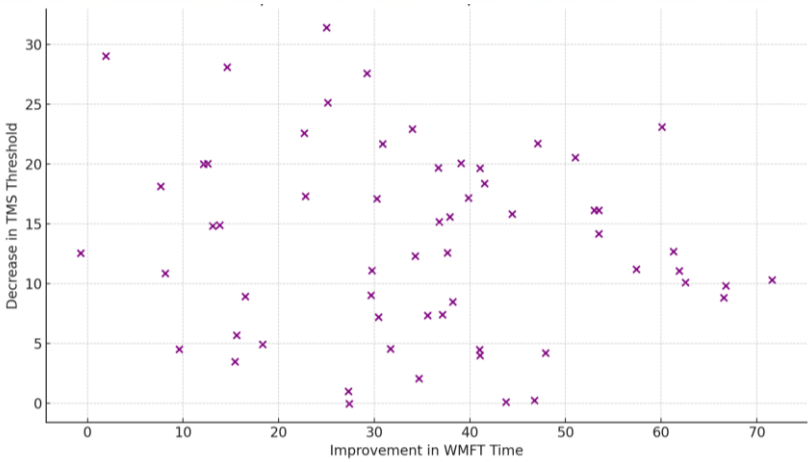

Figure 9: Improvement in WMFT vs. Decrease in TMS Threshold. Scatterplot reveals a positive correlation in improvements.

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AND MEDICAL INNOVATIONS

3. DISCUSSION

When the muscles get stiff after a stroke, it leads to notable changes in the motor cortex, influencing how much recovery takes place. Many stroke patients experience a lower quality of life and face challenges during daily activities due to spasticity (Hyakutake et al., 2021). Among the therapies used, physical therapy, botulinum toxin injections and medications work on reducing spasticity and boosting motor skills (Wang et al., 2020). Botulinum toxin and the use of robots seem to improve the upper extremity function of people who experience chronic stroke spasticity (Paolucci et al., 2021). The majority of people who have experienced a stroke continue to face chronic movement issues, suggesting that different rehabilitative approaches are needed (Chen et al., 2020). Understanding the detailed relationship among muscle spasticity, the motor cortex and rehabilitation is critical (Merians et al., 2020).

Neuroplasticity is a key factor in helping people recover motor skills following a stroke. When areas of the cortex other than the motor cortex handle damaged movements, the motor cortex undergoes restructuring which represents neuroplasticity (Frisoli et al., 2022). The area and placement of the lesion, the time that has elapsed since the stroke and the amount of rehabilitation received play a role in adapting to changes. Increasing the intensity of rehabilitation supports faster improvement in motor skills after a stroke and plays a role in brain plasticity (Lazarević & Živković, 2020). Treatment for stroke patients may include transcranial magnetic stimulation and transcranial direct current stimulation which aim to activate the brain and promote a change in brain cells (Mohan et al., 2022). Apart from these points, robot technology helps reorganize brain activity and repeat training for related tasks.

New studies suggest that treatments that adjust the brain's electrical activity and increase its flexibility can lessen post-stroke stiffness and help recover movement. Neurotechnologies, including robotic systems and electrodes, may make stroke rehabilitation more successful (Micera et al., 2020). Because treatment for gait recovery includes old and new methods, using rehabilitation and combining technologies such as virtual reality and robotics, has shown promise. Additional studies are needed to better understand how to reorganise the motor cortex in stroke victims who experience muscular spasticity and which treatment methods can improve their recovery. With the help of both interdisciplinary care and new technologies, stroke neurorehabilitation is entering a new era that brings hope for a better and quicker recovery to those with this condition (Gunduz et al., 2023). When recovering from stroke damage, the use of artificial intelligence in therapy offers objective assessment and specialised treatment tailored to the individual (Wang et al., 2020).

Telerehabilitation and virtual reality help provide rehabilitation approaches to maximise the chances of stroke recovery (Allegue et al., 2022).

4. CONCLUSION

The care given in the study strongly suggests that patients undergoing motor rehabilitation, involving robots and virtual reality, show huge improvements in movement skills and flexibility after stroke. During the 12-week intervention, those taking part maintained progress, as shown by improvements on WMFT, higher FMA-UE and lower MAS. As these benefits appeared, significant changes were also noticed in brain function such as reduced TMS thresholds and stronger M1 activity detected using functional MRI. Functional recovery in the wake of a stroke can be explained by the evidence from

behavioural and cortical data. Targeting these areas can be very beneficial for therapy, since an association between the lessening of spasticity and improved movements has been reported. When qualitative opinions are added, it is clear that many patients get involved and notice improvements, mainly when using interactive and intelligent rehabilitation technologies. From these findings, it is likely that using technology during rehabilitation can quickly help the brain to heal and boost how stroke survivors feel. Even so, it is important to have customised therapies tailored to each person, based on their brain scans and examinations. Consequently, it shows that stroke recovery can be complicated, hence rehabilitation with the company of a variety of methods, current tools and regular monitoring of the brain works best. Moving forward, efforts should be made to improve patient grouping, examine the overall results over the long run and include more telerehabilitation methods. Relying on precision medicine and scientific approaches to brain repair, these results help advance rehabilitation after a stroke.

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